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# Distinction of directional coupling in sensorimotor networks between active and passive finger movements using fNIRS

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**Abstract:** The purpose of this study is to investigate cerebral cortex activation during active movement and passive movement by using a functional near-infrared spectroscopy (fNIRS). Tasks were the flexion/extension of the right hand finger by active movement and passive movement. Oxy-hemoglobin concentration changes calculated from fNIRS and analyzed the activation and connectivity so as to understand dynamical brain relationship. The results demonstrated that the brain activation in passive movements is similar to motor execution. During active movement, the estimated causality patterns showed significant causality value from the supplementary motor area (SMA) to the primary motor cortex (M1). During the passive movement, the causality from the primary somatosensory cortex (S1) to the primary motor cortex (M1) was stronger than active movement. These results demonstrated that active and passive movements had a direct effect on the cerebral cortex but the stimulus pathway of active and passive movement is different. This study may contribute to better understanding how active and passive movements can be expressed into cortical activation by means of fNIRS.



**OCIS codes:** (170.2655) Functional monitoring and imaging; (170.3880) Medical and biological imaging; (300.0300) Spectroscopy.

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## 1. Introduction

The role of rehabilitation for brain-injured patients is to enable them to perform as much as possible exercise in their daily lives and to reacquire normal motor function [1]. Therapeutic exercise for the recovery motor function is based on the principle and understanding of neuroscience, neurophysiology, and exercise control. Functional behaviors that identify and perform human body position and change, induce changes in the external environment, and interact with each other are analyzed at three levels: action, movement, and neuro-motor process [2]. The mechanism of neuronal motor system was based on the reflex theory, and then the principle of reafference clarified the relationship among efferent motion command, muscle contraction and afferent sensory information processing [3, 4]. Human motor activity can be divided into active and passive movement components. Active movements are those movements made voluntarily via the planning/execution of exercise accompanied by perceptual processing of sensory and proprioceptive information. Passive movement, on the other hand, includes movements generated by external forces and involves only sensory systems [5, 6]. Such exercises are the most commonly used methods of physical therapy for brain injured patients and many studies has proven its effectiveness. Passive movement such as functional electrical stimulation (FES) has been suggested to manipulate external stimuli in order to facilitate motor functions as well as motor execution [7, 8]. FES have been widely used to aid in improving or assisting the functional activities of patients after brain injuries such as post-stroke [9].

Studies have shown that performing of passive movement and active movement of the hand activate cortical activities in different patterns in the sensorimotor areas. A PET study demonstrated that the brain activation associated with active motor task at the elbow was fundamentally the same as that associated with passive movement [10]. A fMRI study reported that no difference was generally detected when contrasting active versus passive hand movements [7]. Some functional near-infrared spectroscopy (fNIRS) studies investigated the cortical activation as well. A fNIRS study investigated the cortical activation pattern for grasping when imagery, motor execution, action observation and passive movement by a functional electrical stimulation and the results demonstrated the considerable differences between these modes [11]. These studies showed only differences of cortical activation between active and passive movement. Because the neurologic recovery of an injured brain itself is also as important as the functional recovery during the early stages of rehabilitation after a stroke, the principle of the neural plasticity may be necessary for passive movements controlled by FES in order to activate the cortical system in view of motor facilitation.

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Recently, researches on neuroscience are progressing not only neuroplasticity but also the role of cerebral cortex in motor nervous system. Neural activity causes hemodynamic responses through neurovascular coupling which is related to changes in concentration of oxygenated (HbO) and deoxygenated (HbR) hemoglobin that can be measured by fNIRS [12, 13]. Therefore, by observing changes in hemoglobin concentration in the cerebral blood flow, neural activity can be investigated. Functional magnetic resonance imaging (fMRI) – which has moderate temporal resolution, high spatial resolution and high expense – is powerful tool and gold standard in non-invasive functional brain imaging. In contrast, fNIRS – relatively small, portable, low cost method providing high temporal and moderate spatial resolution – is an emerging functional brain imaging. Although fNIRS can measure only cortical region, it is a useful tool in many areas of brain research. The brain has large-scale complex networks with, each area organically connected. A variety of cognitive tasks are achieved through the exchange and integration of information between regions within these neural networks. The previous studies have focused on the statistically significant region of brain activity during a particular motor function tasks [14, 15]. Recently, many studies have become interested in describing how different brain areas communicate with each other since such information might help to understand the organized networks of cortical regions [16–18].

In the brain, the term connectivity refers to several different and interrelated aspects of brain organization. A fundamental distinction is that between structural connectivity, functional connectivity and effective connectivity. Anatomical connectivity refers to a network of physical or structural connection between the brain areas, and functional and effective connectivity refers to the functional connection between brain areas based on a particular cognitive process [19]. However, there is a problem in that it is difficult to show the causality between brain areas because the structural and functional connectivity derived from the connectivity model by the strength or correlation of the symmetric relation does not consider directionality.

The purpose of the present study was to investigate representation and connectivity between brain areas with fNIRS. In particular, we wanted to explore the brain mechanism in (i) brain representation of active movement, (ii) brain representation of passive movement, and (iii) difference of connectivity between active and passive movements. Granger causality analysis was used to analyze the effective connectivity among the primary somatosensory cortex (S1), primary motor cortex (M1), and supplementary motor area (SMA).

## 2. Materials and methods

### *2.1 Subjects*

Four healthy right-handed volunteers (four males, mean age 32 years, range: 30~33 years) with no history of neurological, physical, or psychiatric illnesses participated in this study. All participants provided written informed consent and received monetary compensation for their participation. This study was approved by the Institutional Review Board (IRB) of Daegu Gyeongbuk Institute of Science & Technology (DGIST).

### *2.2 Experimental paradigm*

Two stimuli tasks (active and passive movements) were performed with a frequency of 0.5 Hz and the sequence of the trials for every subject was randomly assigned. The fNIRS experiments were arranged in block paradigm. The block design consisted of 7 rest and 6 task periods, each of 20 seconds duration, with alternating rest and task periods. Each trial was repeated three times by each subject. Task and rest periods were cued by beep sound at every start. Active movement of the right hand (flexion/extension) was used for the motor task. Participants were seated on a chair in an upright position and they were asked not to move the trunk. In task phase, subjects were instructed to repeat clenching at 0.5 Hz

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intervals. In rest phase, all subjects were instructed to keep their eyes closed and to relax without performing any movements or any imaginations. During the passive movement by FES, four electrodes were patched on the skin of the right arm at the region of the flexor (two electrodes) and extensor (two electrodes) muscles to make flexion/extension movements of the right hand. Under the passive movement condition (FES), participants were instructed to relax their hand and let it be moved freely. In particular, they were instructed not to help, aid, or support the movement. The participant's hand rested on the table, which was moved as flexion/extension by FES.

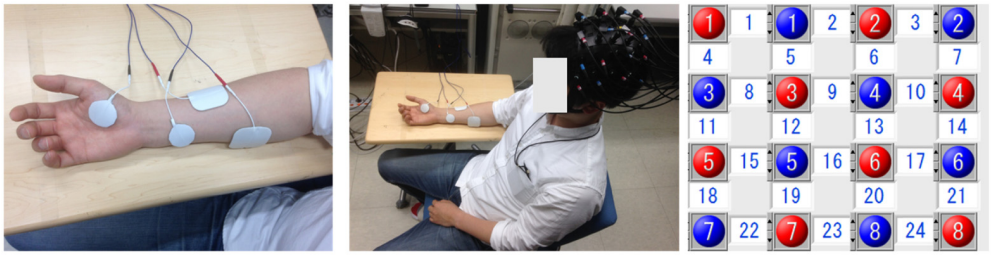


Fig. 1. Experimental setup and channel configurations.

### *2.3 fNIRS procedure*

The fNIRS signal was recorded over the subject's left hemispheres which covered the primary sensory-motor cortex (EEG corresponding areas CPz, CP1, CP3, CP5, Cz, C1, C3 and C5), premotor cortex and supplementary motor area (EEG corresponding areas FCz, FC1, FC3, FC5, Fz, F1, F3 and F5), these areas were likely to be active in response to motor paradigm. A commercial fNIRS system (FOIRE-3000, Shimadzu Co., Japan) was used to measure the hemodynamic responses in this study. This system performed three different wavelengths (780 nm, 805 nm, and 830 nm) continuous-wave (CW) near infrared tomographic measurements at 7.7 Hz sampling rate. Based on the 10-20 international electrode placement system, the 16 optodes (8 sources and 8 detectors) were placed over the subject's head in the primary motor area and primary sensory area. Each detector and the most closely placed light source built a channel. In total there were 24 channels containing information about HbO concentration changes. The inter-optode distance of 30 mm. Figure 1 showed the channels location and experimental setup. The registration of the optode's locations was measured using a 3D position measuring system (FASTRAK, Polhemus, USA).

## 3. Data analysis

### *3.1 fNIRS data processing*

Figure 2 illustrates the block diagram of the fNIRS analysis method for this study. fNIRS non-invasively measures changes in the cerebral blood flow. The principle of measurement was developed by Jobsis, based on the measurements of hemoglobin oxygenation in the cerebral blood flow [20]. A modified Beer-Lambert law formula was used to calculate the HbO concentration [21]. The absorption coefficients of oxygenated hemoglobin and deoxygenated hemoglobin are known. The process of analyzing the fNIRS data was performed using the MATLAB based software package NIRS-SPM [22]. In fNIRS experiments, there often exist global drifts of the optical signal measurements for a variety of reasons, including subject movement, blood pressure variation, long-term physiological changes or instrumental instability. In order to eliminate the global trend and to improve the signal-to-noise ratio, hemodynamic response function (hrf) and wavelet-MDL were employed, as is currently implemented in NIRS-SPM [23–25]. General linear model analysis was applied to analyze the HbO concentration when identifying task-related cortical activity.

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At the group level, one-sample t-tests was performed based on the individual-level beta values to find the activated channels ($p<0.05$, FDR-corrected) [26]. In fNIRS analysis, the spatial registration of NIRS channels to MNI space is available. NIRS-SPM provides functions to transform fNIRS channels in the subject space into the corresponding positions in the MNI space. Also, NIRS-SPM allows the spatial registration of NIRS channels to MNI space without MRI using NFRI' fNIRS tools [27]. The anatomic labelling (Brodmann areas) are listed in Table 1.

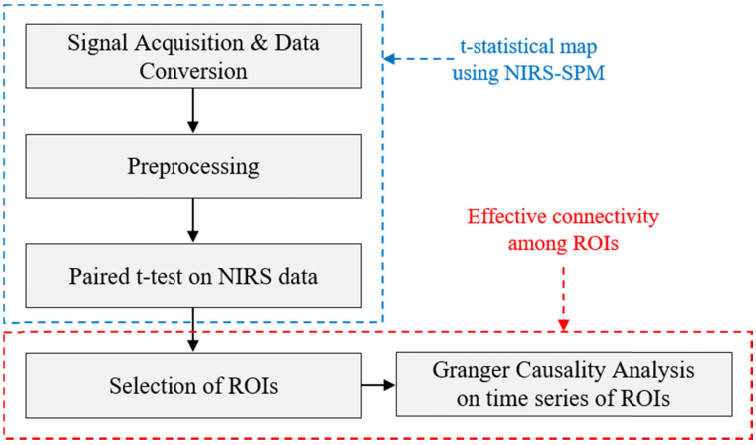


Fig. 2. Block diagram of the fNIRS analysis method.

**Table 1. Anatomic labeling of fNIRS channel position, Brodmann areas (Talairach)**

| NIRS Channel | Brodmann areas | Description (Region of interest) |
|---|---|---|
| 1,2,4,5,6,10 | 1,2,3 | Primary somatosensory cortex |
| 3,7 | 40 | Supramarginal gyrus part of Wernicke's area |
| 8,9,11,12,13,14,15,16,17,18,19 | 6 | Pre-motor and Supplementary motor cortex |
| 20,22,23 | 8 | Included frontal eye fields |
| 21,24 | 9 | Dorsolateral prefrontal cortex |

### *3.2 Functional and effective connectivity analysis*

For each data set, we calculated the ROI-based functional connectivity (FC) with Pearson correlation analysis between two time-series of the measurement channels. We aimed at exploring and comparing the properties of motor-related brain functional networks for active and passive movements, so consistent ROIs (3 ROIs, including M1, S1, and SMA) were selected for active and passive movements to make the brain functional networks. ROIs were defined according to the *t*-values. After that, the averaged time-series were extracted from each ROI of active and passive movement tasks. From this 3 time-series, we can calculate connectivity map which included 3 × 2/2 = 3correlation coefficients.

In order to analyze the effective connectivity of NIRS time series, we adapted Granger causality analysis (GCA), which models one directional causality among multiple time series based on a VAR model [28]. GCA is also used to detect the effective connectivity between brain regions in various measurements, such as fMRI, MEG and EEG. With the value of a time series $x$ at a time slice $t$, $x(t)$ can be estimated using the following two different methods:

$$x(t) = \alpha_0 + \sum_{i=1}^{p} \alpha_i x(t-i) + \varepsilon(t) \quad (1)$$

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$$x(t) = \alpha_0 + \sum_{i=1}^{p} \alpha_i x(t-i) + \sum_{i=1}^{p} \beta_i y(t-i) + \omega(t) \quad (2)$$

Maximal model order $p$ is determined by using the Bayesian Information Criterion (BIC) [29]. In this study, the Granger causality is evaluated using [30]

$$F \equiv \frac{(RSS_0 - RSS_1) / P}{RSS_1 / (T - 2P - 1)} \quad (3)$$

where

$$RSS_0 = \sum_{t=1}^{T} \varepsilon(t)^2 \text{ and } RSS_1 = \sum_{t=1}^{T} \omega(t)^2 \quad (4)$$

where $T$ is the number of observation. To assess the statistical significance of the estimated Granger causality, we adopted the $F$-test with the null hypothesis, $H_0 : \beta_i = 0$. In order words, $y(t)$ does not influence the generation of $x(t)$. On the contrary, if the null hypothesis is rejected, that is, $F$ is sufficiently large; we can conclude that $y(t)$ causes $x(t)$. A higher $F$-score means a stronger prediction of Granger causality between the two time-series. The window size for the causality evaluation was set to be 40s starting from the 10 s before stimulation onset time. To analyze the connectivity among brain regions, block average of fNIRS signals over all subjects was done along the stimulation blocks for each individual subjects. In this study, HbO was used to analyze the brain activation and directional coupling of cortical areas because it is the most sensitive indicator of changes in the regional cerebral blood flow.

## 4. Results

In this study, in order to investigate the cortical activation and connectivity among brain areas during active movement versus passive movement by FES with fNIRS. The changes in HbO concentration was measured for brain activation analysis. Also, Granger causality analysis was applied to fNIRS data to evaluate effective connectivity among the ROIs.

### *4.1 Brain activation*

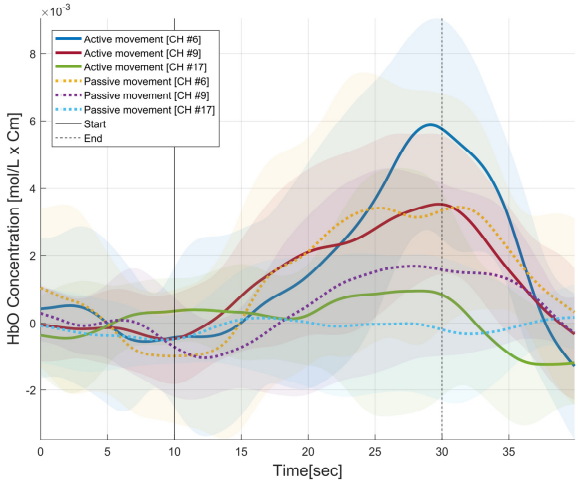


Fig. 3. Representative plots of changes in oxy-hemoglobin concentration in S1, M1, and SMA locations on the left hemisphere of the brain.

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Figure 3 shows the HbO concentrations during the active movement (red line) and passive movement (blue line). Black lines indicate the task start (solid line) and end (dashed line), respectively. The S1, M1, and SMA regions related to hand movements was selected as the ROIs and the brain activity were compared. All movement modes commonly activated the S1 and M1 than SMA. Passive movement shows basically the same pattern of activation as that of the active movement. And active movement activation was stronger than the passive movement. Table 2 shows the MNI coordinates and statistical *t*-value of the ROIs during the task. Active movement showed significant activation in all ROIs and the highest *t*-value was found at M1. Under the passive movement, significant activation was observed in the S1 and M1 and the highest *t*-value was found at S1.

**Table 2. Brain activation from ROIs during tasks**

| Task | Region of interests | MNI coordinates | | | *t*-value ($p<0.05$) |
|---|---|---|---|---|---|
| | | x | y | z | |
| **Active** | S1(6) | –46 | –33 | 67 | 4.90 |
| | M1(9) | –35 | –19 | 73 | 10.57 |
| | SMA(17) | –49 | 7 | 52 | 2.25 |
| **Passive** | S1(6) | –46 | –33 | 67 | 6.28 |
| | M1(9) | –35 | –19 | 73 | 2.62 |
| | SMA(17) | –49 | 7 | 52 | 0.70 |

### *4.2 Connectivity*

Figure 4 shows the HbO functional connectivity among the ROIs. The whiter pattern shows strong functional connectivity. The results show that the time-series between S1 and M1 are highly correlated in the active and passive movements, and the correlation between the SMA and other regions is low. The degree of connectivity between ROIs is shown in Table 3 as a correlation coefficient. Figure 5 shows the effective (causal) connectivity among the brain areas of the S1, M1, and SMA. In the Fig. 5, the significant causality is indicated by solid line and the non-significant values are indicated by dotted line. Granger causality analysis was applied for the effective connectivity. The strength of the Granger causality was presented using the *F*-value. A larger *F*-value means that there is a strong oriented influence between the two time-series. The results show statistically significant Granger causality values between S1 and M1 as well as between SMA and S1 connections and did not show statistically significant causality values from M1 to S1 connections during the active movement. In contrast, the Granger causality from SMA to S1 and M1 was weaker than motor execution and stronger than motor execution between S1 and M1 during the passive movement. The causal degree measured using the *F*-score is listed in Table 4. Specifically, we found that during the active movement, there was a stronger influence from SMA to S1 and M1 while within the passive movement, there was a stronger influence from S1 to M1.

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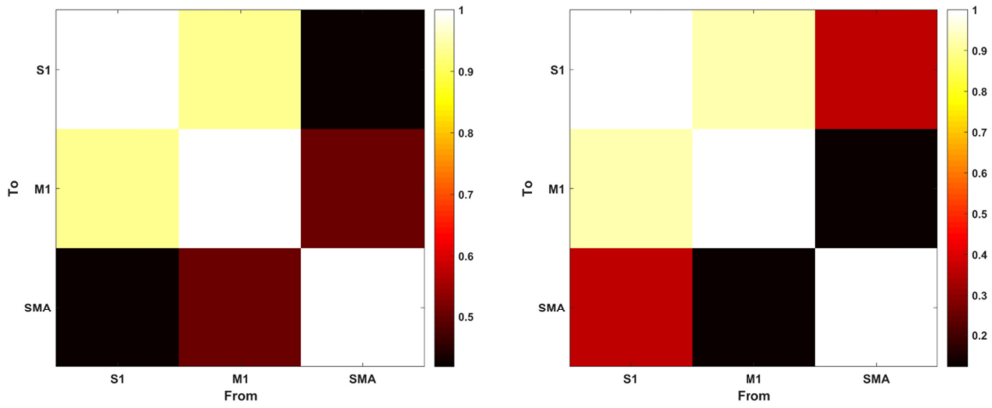
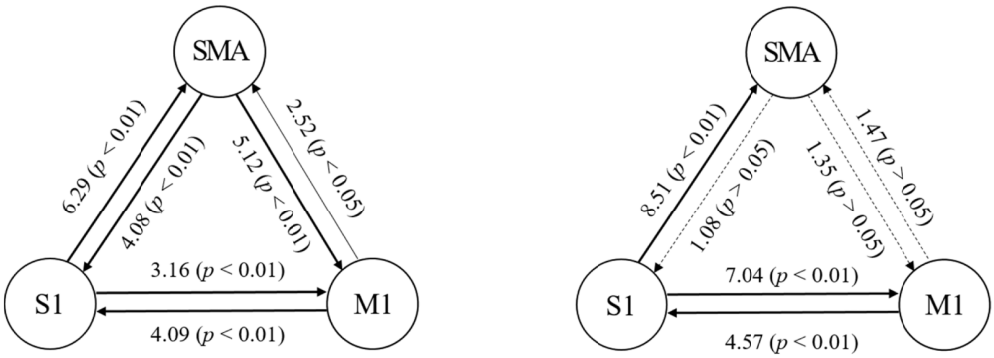



(a) Active movement (b) Passive movement

Fig. 4. Illustration of ROI-based functional connectivity map. White color denote a strong functional connectivity, while dark colors denote weak functional connectivity between ROIs.

**Table 3. The degree of functional connectivity**

| Task | ROIs | Corr. Coeff | Task | ROIs | Corr. Coeff |
|---|---|---|---|---|---|
| Active movement | S1 & M1 | 0.93 | Passive movement | S1 & M1 | 0.92 |
| | S1 & SMA | 0.41 | | S1 & SMA | 0.35 |
| | M1 & SMA | 0.5 | | M1 & SMA | 0.12 |




(a) Active movement (b) Passive movement

Fig. 5. The Granger causality values from two tasks. The strength of the Granger influence is presented using the *F*-score, and arrow thicknesses.

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**Table 4. The degree of the significant causal interactions (*F*-score)**

| Active movement | | | Passive movement | | |
|---|---|---|---|---|---|
| From | To | *F*-score | From | To | *F*-score |
| S1 | M1 | 3.16 | S1 | M1 | 7.04 |
| | SMA | 6.29 | | SMA | 8.51 |
| M1 | S1 | 4.09 | M1 | S1 | 4.57 |
| | SMA | 2.52 | | SMA | 1.47 |
| SMA | S1 | 4.08 | SMA | S1 | 1.08 |
| | M1 | 5.12 | | M1 | 1.35 |

## 5. Discussion and conclusion

In this study, cerebral cortex activation and connectivity among the M1, S1, and SMA were investigated during performance of active and passive movement of the right hand fingers. HbO was used to measure hemodynamic changes in the cerebral cortex. HbO is the most commonly used parameter of fNIRS, measures neural activity indirectly by detecting hemodynamic changes in the underlying cerebral cortex [31]. The rationale for this estimation is based on the concept that neural activation in response to external stimuli results in increased energy demands in the activated area. Consequently, an increasing change in HbO occurs during neural activation [32]. In both movement modes, we observed cerebral activation in the hand somatotopy of the contralateral M1, S1. However, passive movement elicited a weak brain activation compared with active movement. These findings are consistent with the results of a previous functional neuroimaging studies that reported the M1 as well as S1 were activated by sensory stimuli such as electrical stimulation or proprioceptive input [33, 34].

Previous studies on neuroscience using functional brain imaging technique has mainly analyzed data in terms of functional segregation [35, 36]. Many studies have also attempted to reveal whether or not activation occurred at specific locations during specific stimulation [37, 38]. In recent years, it has become possible to study functional integration based on functional segregation. In other words, it has become possible to study which activation pattern appears in each region or between regions during a specific cognitive function. Despite of the wide-spread use of fMRI-BOLD to investigate connectivity, many recent studies have demonstrated that fNIRS can be considered as one of the reasonable alternatives [39–41].

Evidences from previous studies have demonstrated the importance of SMA in brain. A study on healthy subjects suggested that the stronger coupling between contralateral SMA and M1 could enable increased motor performance of hand movements [42]. In this study shows the strong correlation between S1 and M1 in the functional connectivity, but the correlation with SMA was not confirmed during two movement modes. Therefore, we tried to analyze the causality by effective connectivity between ROIs. Among the various analytical methods for functional integration, Granger causality analysis (GCA) – which describes a statistical interpretation of causal interactions between sets of time series – is often employed to measure the effective connectivity in this study. The Granger causality analysis is usually performed at the level of measured hemodynamic signals, such as HbO and HbR responses [43, 44]. However, connectivity estimates at the level of hemodynamic measurements are not reflect the connectivity changes at the neuronal level, because the hemodynamic response to neuronal activation depends on the changes in cerebral blood flow and oxidative metabolism, and also on the changes in cerebral blood volume [45]. This complex interplay between processes can cause functional connectivity to differ with the type

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of hemoglobin changes, while underlying interactions between neuronal populations do not vary [46].

In this study, we investigated the connectivity within 3 ROIs (M1, S1, SMA) by analyzing the effective connectivity between active and passive movement using GCA. In active movement phase, significant causality influences were observed from SMA to M1 and S1 and between M1 and S1, which validate that in the active movement will yield the activation in SMA because it is involved in planning movements and in coordinating movement that involve both hands [47].

In addition, Granger causality influence was also observed between M1 and S1 during the passive phase. Functional electrical stimulation (FES) appears to work for the brain through the combined stimulation of sensory and motor stimuli, and the main stimuli pathway is sensory input. The pathway of M1 activation by somatosensory stimuli has not been clearly elucidated. Previously, it was assumed that the afferent input reached M1 though the S1 [38]. Previous studies of active movements showed the participation of the primary sensorimotor cortex (SM1), lateral premotor cortex, supplementary motor area (SMA) [48, 49]. As such, brain regions associated with active movement likely included most of the motor system and was consistent with previous studies. Cortical activation of the proprioception elicited by the passive movement included the contralateral S1. The active movement includes a voluntary aspect, expected to be mainly related to the somatosensory component due to proprioceptive feedback and exteroceptive sensory afferent. On the other hand, passive movement is expected to consist of only sensory component and thus of a sensitive cortex activity. In the study of passive movement, the cerebral blood flow were measured in the corresponding area of the brain using positron emission tomography-computed tomography (PET-CT) during active or passive movement of elbow flexion/extension [10]. Therefore, we believe that our results indicating activation and connectivity within ROIs by the active and passive movement are consistent with those reported in previous studies. As a result, an increase in cerebral blood flow was observed in the contralateral sensory and supplementary motor area. fNIRS study reported the passive movement conducted by FES activated an contralateral sensorimotor of brain areas [11]. An fMRI study showed the activation in the sensorimotor area for passive movement conducted by an examiner [10]. The results of previous study are consistent with the result of present study, which suggests that active movement is more effective than passive movement. Because the active movement uses a proprioceptive feedback and exteroceptive input in comparison with passive movement using only somatosensory sense. Our results suggest that active and passive movement could induce cortical activation. Therefore, we believe that our results would be helpful for rehabilitation research. In addition, fNIRS could be a useful tool in research on the cortical activation. Further studies on the clinical effects of patients with brain injury are also recommended.

In the current study, we investigated the brain activation and applied the Granger causality analysis to fNIRS data to investigate the effective connectivity between cortical areas during active and passive movements. The experimental results showed that the brain activity during passive movements by FES was similar to that of active movement. However, there was a difference in effective connectivity between ROIs. These results provide an integrated and interactive view of the brain network during finger movements. Although, fNIRS has lower spatiotemporal resolution than fMRI, our findings were consistent with results from previous studies in fMRI. fNIRS is a suitable tool for evaluating brain activation and connectivity. Moreover, it can be a potentially powerful non-invasive brain monitoring modality for diagnosis and evaluation of motor function for rehabilitation medicine.

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## Disclosure

The authors declare that there are no conflicts of interest related to this article.